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Stricker, Robert John

Monterey, California: U.S. Naval Postgraduate School

NORMALIZED SPECTRA OF TURBULENT FLUCTUATIONS OVER OCEAN WAVES

Robert John Stricker

NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

NORMALIZED SPECTRA OF TURBULENT FLUCTUATIONS

OVER

OCEAN WAVES

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Normalized Spectra of Turbulent Fluctuations
over
Ocean Waves

by

Robert John Stricker
Lieutenant, United States Navy
B.S., University of Minnesota, 1965

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ABSTRACT

Spectral and cospectral analyses are performed on turbulence data obtained over natural ocean waves during BOMEX. Results are obtained for normalized spectra and cospectra. Significant scatter is observed throughout the spectra and cospectra with a larger degree of scatter in the low frequency range. Kolmogorov's -5/3 power law is found to describe the longitudinal and vertical velocity spectra in the high frequency range. However, it is not applicable to the lateral velocity spectra while results for the temperature spectra are inconclusive. Monin-Obukhov similarity theory well describes the vertical velocity spectra yet its application to horizontal velocity spectra is doubtful. Similarity theory does not seem to adequately describe the uw cospectra. Results from comparing similarity theory to temperature spectra and wT cospectra indicate the presence of an influence not accounted for by similarity theory. When compared, uw and wT cospectra are found to be significantly different. All computed spectra and cospectra are found to have a relatively larger amount of energy in the low frequency range than their respective over land spectra and cospectra.

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I. INTRODUCTION

The ability to make short range atmospheric predictions with a reasonable degree of success has shown great progress over the past two decades. The desire to extend these predictions has recently led to an increased interest in the near surface boundary layers over the oceans. For example, Zilitinkevich (1969) has stated the extension of forecast ranges will require a more comprehensive understanding and a more accurate description of the turbulent boundary layers between the atmosphere and the oceans.

In order to gain understanding of the mechanics of small-scale air-sea interaction processes, it is important to analyze measurements of turbulence in the atmospheric boundary layer. Summaries of research done, primarily over land, have been published by Busch and Panofsky (1968) and Panofsky (1969). Until recently, the description of turbulence in the atmospheric boundary layer over the ocean has been limited by the availability of data. In 1969, significant progress with respect to observational studies occurred as a result of the "Barbados Oceanographic and Meteorological Experiment" (BOMEX).

BOMEX took place in the Atlantic Ocean east-northeast of Barbados, West Indies. The experiment was perhaps one of the largest experimental research programs of this kind ever undertaken. One of the over 80 subprograms, titled "sea-air

interaction," is significant to this study in that it dealt with the measurement of wind and temperature parameters in the near surface layer of the atmosphere. Of the various oceanic platforms used to collect data for this subprogram, the data from the "Floating Instrument Platform" (FLIP)[1] will be considered in this study.

The primary purpose of this study is to examine the consistency between normalized variance spectra and between normalized covariance spectra, subsequently to be referred to as spectra and cospectra, obtained from the velocity and temperature data collected near the surface. In addition, proposed universal forms of these spectra are discussed.

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[1] FLIP was developed by the Marine Physical Laboratory of the University of California, San Diego and Scripps Institute of Oceanography. For more information on FLIP see Bronson and Glasten (1965).

II. BACKGROUND

With the recent increase of data collection in the atmospheric boundary layer, a number of papers have emerged on the topics of normalized spectra and possible universal forms. Treatments by Panofsky et al. (1968), Phelps and Pond (1971), Volkov (1969) and others have yielded evaluations of existing theory and additional development of a universal form for spectra of turbulence within the boundary layer.

A. THEORETICAL BACKGROUND

Two theories have been used to describe normalized spectra. The Kolmogorov -5/3 power law (for the inertial subrange) and Monin-Obukhov's similarity theory are both discussed by Lumley and Panofsky (1964).

Kolmogorov's theory of local isotropy for the inertial subrange is based upon two assumptions. First, turbulence is considered locally isotropic at sufficiently small scales. Second, at a sufficiently high Reynolds number there is assumed to exist a range of wave numbers in which no significant production or dissipation of energy takes place. This range of wave numbers is called the inertial subrange. With the argument that energy inflow from larger scales of turbulence equals that transferred to smaller scales, the universal form of the spectra as represented by Lumley and

Panofsky (1964) is predicted to be:

$$E(k) = a \; \varepsilon^{2/3} \, k^{-5/3} \qquad (2.1)$$

for horizontal and vertical spectrum where E(k) is the spectrum, a is a universal constant (not as yet well defined), ε is the dissipation rate of turbulent energy heat and k is the wave number. The Universal from of temperature spectra as represented by Lumley and Panofsky is predicted to be:

$$E(k) = b \; N \; \varepsilon^{-1/3} \, k^{-5/3} \qquad (2.2)$$

where N is the dissipation rate of turbulent temperature fluctuations and b is a universal constant (not as yet well defined).

Monin-Obukhov similarity theory assumes the structure of the turbulence is determined by the turbulent flow itself, except for scaling factors. Thus, a friction velocity $u_*^2 = \overline{-u'w'}$ exists for boundary layer flow which typifies the turbulence and is independent of height. Likewise, a characteristic length determined by the distance from the boundary or by the flow stability and the turbulence is assumed existent. Universally related dimensionless velocities and lengths may then be formed using friction velocity and characteristic length values.

For time spectra, similarity theory predicts the following expressions which relate the velocity and temperature spectra and cospectra to the basic parameters in

the boundary layer.

$$nS_u(n) = u_*^2\ \phi_1(f, z/L)\ , \qquad (2.3)$$

$$nS_v(n) = u_*^2\ \phi_2(f, z/L)\ , \qquad (2.4)$$

$$nS_w(n) = u_*^2\ \phi_3(f, z/L)\ , \qquad (2.5)$$

$$nS_T(n) = T_*^2\ \phi_4(f, z/L)\ , \qquad (2.6)$$

$$nC_{uw}(n) = u_*^2\ \phi_5(f, z/L)\ , \qquad (2.7)$$

$$nC_{wT}(n) = \overline{w'T'}\,\phi_6(f, z/L)\ , \qquad (2.8)$$

where S(n) and C(n) are the one-dimensional spectra and cospectra respectively, identified by a subscript for the three velocity components (u - longitudinal, v - lateral, and w - vertical) and temperature (T), n is the frequency in hertz, u_* is the friction velocity, and $\phi_i(f, z/L)$ are yet unknown universal functions. f is the non-dimensional frequency given by $nz/\overline{U}$ where $\overline{U}$ is the mean wind speed at the height of observation and z is the height above the surface. L is the Lettau-Monin-Obukhov length:

$$L = -\frac{u_*\ \overline{T}}{0.4\ g\ \overline{w'T'}}\ . \qquad (2.9)$$

T_* is a scaling factor with the dimensions of temperature defined by:

$$T_* = -\frac{\overline{w'T'}}{0.4 u_*} \qquad (2.10)$$

where the factor 0.4 represents the von Karmen constant.

B. OBSERVATIONAL BACKGROUND

The consistency of spectra within specific studies has been strikingly uniform. In general, the high frequency range of combined spectra has little scatter while the low frequency range has a significantly larger amount of scatter. Volkov (1969) attributed the scatter in the low frequency spectral region to the disturbing influence of sea swell. However, Berman (1965) noted the same phenomena in spectra over land.

With regard to Kolmogorov theory, considerable evidence now exists, as noted by Panofsky (1969), to verify that the -5/3 power law fits spectra of the horizontal velocity components within the inertial subrange for neutral and unstable air provided the height is equal to or larger than the wavelength. Taylor's hypothesis, discussed by Lumley and Panofsky (1964) gives the wavelength as $\overline{U}/n$. The apparent extension of the -5/3 law below the inertial subrange may be an error of interpretation as noted by Pond et al. (1966) or suggest a continuity of the -5/3 law to wave numbers higher than those out of the measured wave number range, as suggested by Busch and Panofsky (1968).

Application of the -5/3 law to temperature spectra has met with positive results. Volkov (1969) observed a fairly clear linear interval where the -5/3 law dependence of over ocean spectra on the frequency is followed. Similar results for over ocean temperature spectra were noted by Pond et al. (1966). Work done by Panofsky et al. (1968) on over land

spectra showed the existence of a frequency interval over which the -5/3 law applied. Utilizing two sets of temperature data collected by University of Washington personnel on board FLIP during a pre-BOMEX trial and during BOMEX, Phelps and Pond (1971) found spectra for the pre-BOMEX data to follow the -5/3 law but the temperature spectra for the BOMEX data, in the same frequency range, had not yet reached a sufficiently high frequency where the -5/3 law applied.

The fit of the -5/3 law to vertical velocity spectra, however, is not yet well defined. Panofsky (1969) suggests that local isotropy for vertical velocity spectra exists at much shorter wavelengths than those for which horizontal velocity components obey the Kolmogorov law. In measurements made by Weiler and Burling (1967), the relation $S_w(k) = 4/3 \quad S_u(k)$ showed local isotropy was approached but not reached at scales a decade from those of maximum dissipation. Spectra published by Panofsky et al. (1967) show evidence of a -5/3 region and the results of Volkov show an extremely clear -5/3 region. However, Busch and Panofsky (1968) found indications of a slope with a larger absolute value than 5/3. As a possible explanation, Lumley (1964) suggests the existence of a buoyant subrange for f much greater than 1 where the slope of spectra may be on the order of -2.

With regard to Monin-Obukhov similarity theory, horizontal velocity spectra are not adequately described. Calder (1966) demonstrated the illegitimacy of applying

similarity theory to horizontal velocity spectra theoretically. This was verified by Busch and Panofsky (1968) who observed the frequency of the maximum spectral value not to vary linearly with height, contrary to similarity theory. Panofsky et al. (1968) suggest the low frequencies of horizontal velocity components are influenced by large quasi-horizontal "eddies" which are sensitive to the large scale features of the terrain not described by similarity theory. Also, a distinctive feature of horizontal velocity spectra as noted by Lumley and Panofsky (1964) is the independence of the high frequency portion of the spectra of stability while the low frequency portion is strongly influenced by stability. In this regard, the lateral spectra are more sensitive than the longitudinal spectra.

The use of Monin-Obukhov similarity theory to describe vertical velocity spectra has, however, met with some positive results. Panofsky and McCormick (1960) found the form of vertical velocity spectra to be independent of stability, roughness, and wind speed and for near-neutral and unstable conditions, essentially invariant up to heights on the order of 100m. Busch and Panofsky (1968) limited the height of invariance to 50m noting that as the height above the surface increases, similarity theory breaks down. They also observed the spectra to vary only with z/L, and above 50m the spectra shifted toward larger frequency. Suggested universal forms will be noted later.

Observations relating Monin-Obukhov similarity theory to temperature spectra are not in total agreement. Lumley and Panofsky (1964) found the high frequency behavior of temperature spectra to be well accounted for by similarity theory. In addition, work done by Panofsky et al. (1968) resulted in a suggested universal form which will be discussed later. However, the results of Phelps and Pond (1971) showed the temperature spectra to be influenced by radiative transfer which is an effect not accounted for by similarity theory. Because radiative transfer is in part dependent on the moisture content of the air, Phelps and Pond (1971) did not discount the applicability of similarity theory to temperature spectra under conditions of low absolute humidity.

In their discussion of uw cospectra, Lumley and Panofsky (1964) found agreement between Monin-Obukhov similarity theory and uw cospectra. Panofsky et al. (1967) found no indication of any systematic changes in the uw cospectra with height or between sites--an observation also made by Lumley and Panofsky. Similar results are described by Kaimal et al. (1972).

The ability to describe wT cospectra using Monin-Obukhov similarity theory has met with results similar to those discussed for temperature spectra. Lumley and Panofsky (1964), Panofsky et al. (1968), and Kaimal et al. (1972) found agreement between wT cospectra and similarity theory. The disagreement observed by Phelps and Pond (1971) is the same as previously noted for the temperature spectra.

A controversy exists as to whether uw and wT cospectra are similar or different. Lumley and Panofsky (1964) point out that a difference between the cospectra would suggest the transports of momentum and heat are dissimilar and thus the exchange coefficients for both could also be different. The results obtained by Panofsky et al. (1968) showed no significant difference between uw and wT cospectra. The uw and wT cospectra analyzed by Kaimal et al. (1972), however, did show a difference from which it was concluded that small eddies transport heat more effectively than momentum and large eddies ($f < 1.0$) transport heat less effectively than momentum.

When comparing horizontal and vertical spectra over land to those over sea, Busch and Panofsky (1968) found spectra over the sea had more energy in the low frequencies. Utilizing evidence of the existence of large "eddies" near the ground, Panofsky (1969) suggests these "eddies" remain intact as they progress over the ocean or smooth terrain and are broken up over rough terrain. Intact, they would add low-frequency energy not described by similarity theory.

III. MEASUREMENTS AND ANALYSIS

A. MEASUREMENTS

The data used in this study were obtained, aboard FLIP, by University of Michigan personnel who collected over 54 hours of data in 40 separate observational periods in the last two weeks of May 1969. The instruments utilized to measure the three fluctuating velocity components (u, v, and w) and temperature fluctuations were mounted on a vertical mast at the 2, 3, 6, and 8 meter levels. The mounting arrangement of the instruments and their orientation with respect to the wind direction is indicated in Figure 1.

The velocity components were measured with linearized hot film, constant temperature anemometer systems. Temperature fluctuations were measured with a fine resistance wire operated in a wheatstone bridge.

The fixed orientation of the mast with respect to FLIP's orientation made it near impossible to maintain the sensors in a mean level position. Provisions to correct for this were made during analyses. However, the influence of FLIP's motion on the data has not been accounted for but has been briefly noted in the discussion of the results.

Sensor outputs were recorded by frequency modulation on two seven channel, magnetic tape recorders using one-quarter inch magnetic tape. Details on sensors and recording equipment are delineated by Portman et al. (1970).

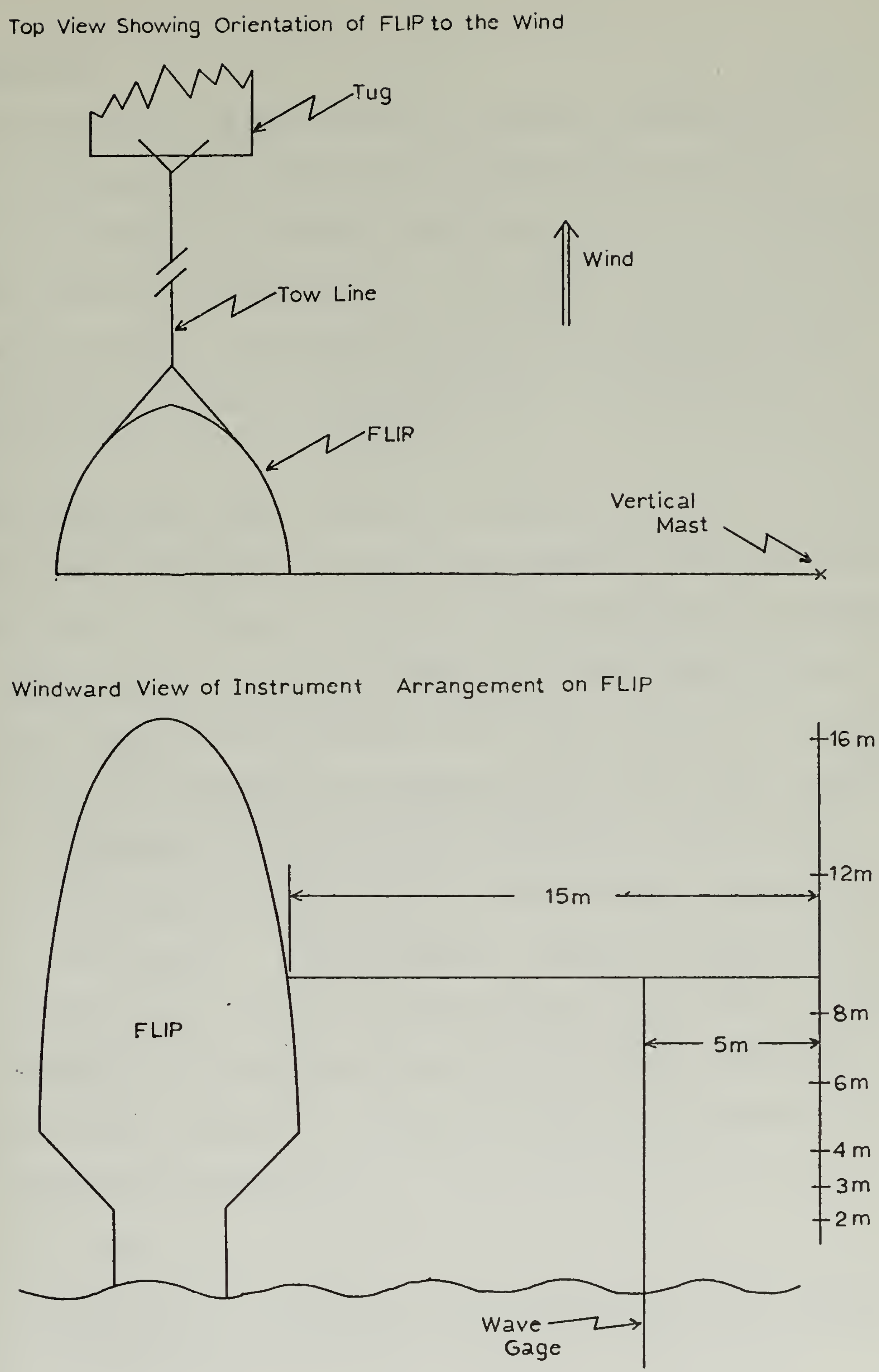

Figure 1. Orientation of FLIP to the wind and sensor location.

B. ANALYSIS

The data preparation[1] prior to spectral analysis consisted of digitizing, reduction of digitized records by numerical filtering, applying direction cosines to determine the wind velocity components (u, v, and w), scaling data to engineering units, and computation of zero-lag statistics. These initial procedures appear in the flow diagram in Figure 2.

The subsequent steps taken to reduce the data and obtain variance and covariance spectral estimates are discussed by Bingham (1972). A brief outline of the procedures[2] follows. First, an 11 weight low-pass numerical filter was applied to reduce the sampling rate from 25 to 5 data points per second. Next, means and trends were removed so that the time series could be considered statistically stationary. Following removal of erroneous data points, a data window was applied to each time series. A fast-Fourier transform algorithm was then applied. The resulting coefficients were used to compute the variance and covariance spectral estimates. Finally, the estimates were reduced to 128 data points by averaging over the neighboring harmonics.

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[1]All procedures utilized in the initial data preparation were developed by the Department of Meteorology and Oceanography, University of Michigan, under the direction of Professor D.J. Portman.

[2]All of these computations were performed on the IBM-360 computer in the W.R. Church Computer Facility at the U.S. Naval Postgraduate School, Monterey, California.

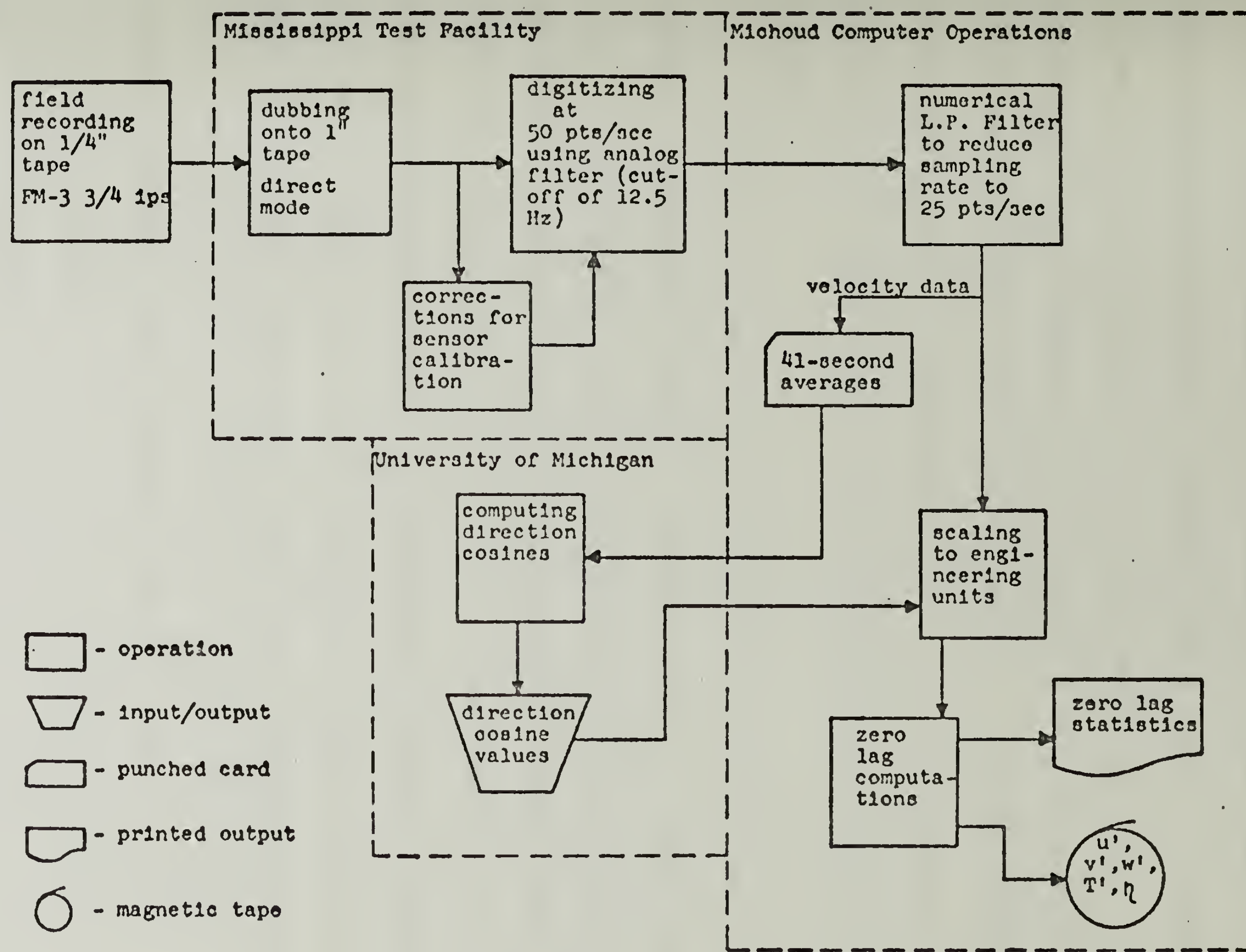

Figure 2. Initial data processing flow diagram from Portman et al. (1970).

In addition to these results, spectral and cospectral estimates from higher sampled records, computed by Professor K.L. Davidson for 11 minute sub-periods, were utilized to extend the non-dimensional frequency range from f = 1 to f = 10. These spectra and cospectra were computed in the same manner as outlined above except that a low-pass numerical filter with a cut-off of 12.5 Hz was utilized. Spectral estimates from consecutive 11 minute sub-periods were then averaged together linearly to equal the time interval for the data processed by the method using the 11 weight low-pass numerical filter, i.e. 5 sub-periods would equal a 55 minute period.

Fifteen of the 40 observational periods were chosen for further spectral analysis in this study. The first 36 of the 128 spectral estimates obtained for each period were discarded due to insufficient spectral resolution. The remaining data points were further reduced to 30 by linearly averaging sets of three consecutive points. The 93 data points for the "12.5 Hz" estimates, minus the first two points and the last point, were also reduced to 30.

With respect to normalization, the horizontal and vertical velocity spectra were normalized by the variance of the vertical velocity. This method of normalization is discussed by Panofsky (1969) and Miyake et al. (1970). No attempt was made to adjust the magnitude of the variance of the vertical velocity as suggested by Panofsky. The temperature spectra were normalized by the variance of the temperature, a

procedure used by Miyake et al. (1970) and Phelps and Pond (1971). The uw and the wT cospectra were normalized by the friction velocity squared and $\overline{w'T'}$ respectively. Normalized spectra and cospectra were plotted against the previously defined non-dimensional frequency (f).

All plots were made on log-log scales. Since all $\overline{w'T'}$ values were negative, taking the log of the normalized wT cospectra presented no difficulty. However, the normalized uw cospectra for seven of the 15 periods were positive above f = 1. Thus, taking the log of minus the normalized cospectra necessitated the elimination of the now negative data points above f = 1.

A final step was to combine the results from the process utilizing the 11 weight low-pass filter and those from the high sampling rate (11 minute) computation. The respective plots were overlayed and aligned by eye. The overlapping regions of the respective plots (approximately two decades) coincided so closely that no doubt exists as to the validity of the procedure.

IV. PRESENTATION OF RESULTS

Normalized spectra and cospectra for fifteen of the 40 observational periods will be presented in this section. A brief meteorological summary of these periods is shown in Table 1. Included in the table is a listing of the plotting symbols used for each period.

The thermal stratification of the air was stable for all periods thus no consideration was given to separately analyzing periods according to any specified stability ranges. The height of measurement was not found to influence the results. However, as the heights ranged from three to eight meters, no significant affect was expected.

Each of the velocity spectra has a noticeable peak in the non-dimensional frequency range $f = .07$ to $f = .2$ as seen in Figures 3, 4, and 5. This narrow band of increased energy is believed due to the influence of FLIP's motion as well as wave related motion. Although the influence of FLIP's motion is believed to have contributed energy throughout each spectrum, a significant portion of the energy is expected to be within the noted frequency range. As seen in Figures 6, 7, and 8, the influence of FLIP's motion is not discernible in the normalized temperature spectra, uw cospectra and wT cospectra. Subsequent discussions of the spectra will disregard the peak.

METEOROLOGICAL SUMMARY OF ANALYZED PERIODS

Period Number	Date (1969)	Start Time (GMT)	Period Length (min.)	Height Analyzed (m)	$\overline{U}$ (mps)	u_* (cm/sec)	σ_w (cm/sec)	σ_T (°C)	$\overline{w'T'}$	z/L	$H_{1/3}$ (m)	Plotting Symbol
A-10	19 May	0308	80	6	10.5	28.9	24.9	5.8	-.28	.01	3.3	
A-11	19 May	0546	82	6	9.3	34.1	25.1	7.4	-.55	.01	3.3	
A-12,1	19 May	0754	55	6	10.1	32.5	37.8	9.3	-.15	.003	3.3	
A-13	19 May	0948	77	6	8.5	31.0	15.3	5.4	-.05	.04	3.4	
A-16	19 May	1843	80	8	10.0	24.2	30.0	9.1	-.57	.037	3.4	
A-22,1	26 May	1432	34	8	8.8	14.4	31.4	5.3	-.46	.14	2.9	
A-22,2	26 May	1512	41	8	9.2	20.8	37.1	26.9	-.90	.09	3.0	
A-23,1	26 May	1706	36	8	9.7	16.4	31.5	4.7	-.53	.11	3.0	
A-26	27 May	0501	53	8	12.0	16.4	38.8	8.3	-.98	.20	3.0	
A-27	27 May	0901	82	8	12.3	31.4	30.8	6.8	-.33	.01	3.1	
A-28	27 May	1058	82	8	13.3	33.8	37.8	6.6	-.60	.014	3.2	
A-30	27 May	1616	82	8	11.1	28.0	42.4	6.8	-.20	.01	3.2	
A-35	28 May	0934	81	8	12.9	17.4	46.8	7.7	-.50	.18	3.2	
A-39	28 May	1754	82	3	11.0	17.4	41.9	7.1	-.99	.09	3.3	
B-16	19 May	1843	80	3	10.4	24.2	63.9	NA	NA	.006	3.4	

A. HORIZONTAL VELOCITY SPECTRA

Normalized longitudinal (u) and lateral (v) velocity spectra are shown in Figures 3 and 4 respectively. The scatter in the lower frequencies is significantly greater than that in the higher frequencies. The degree of scatter throughout the spectra especially that noted in the v spectra was not expected nor can it be explained.

The straight line drawn on each plot has a slope of -2/3 which corresponds to the Kolmogorov -5/3 power law since the plots are of the form $n \cdot \phi(n)$. The u spectra follow the -5/3 law from $f = .2$ to $f = 6$ quite well. Above $f = 6$, there is a change in the slope of the spectra due to the low-pass filter applied during the preliminary analysis. Unlike the u spectra, there seems to be no relation between the -2/3 law and the v spectra. The v spectra do suggest a slope on the order of -1/2 between $f = .2$ and $f = 3$ but then drop off similar to the u spectra.

As has been previously noted by Panofsky et al. (1968) and Busch and Panofsky (1968), the low frequency portion of the horizontal velocity spectra does not follow Monin-Obukhov similarity theory. The amount of scatter observed in the spectral low frequencies could not be predicted by the similarity theory.

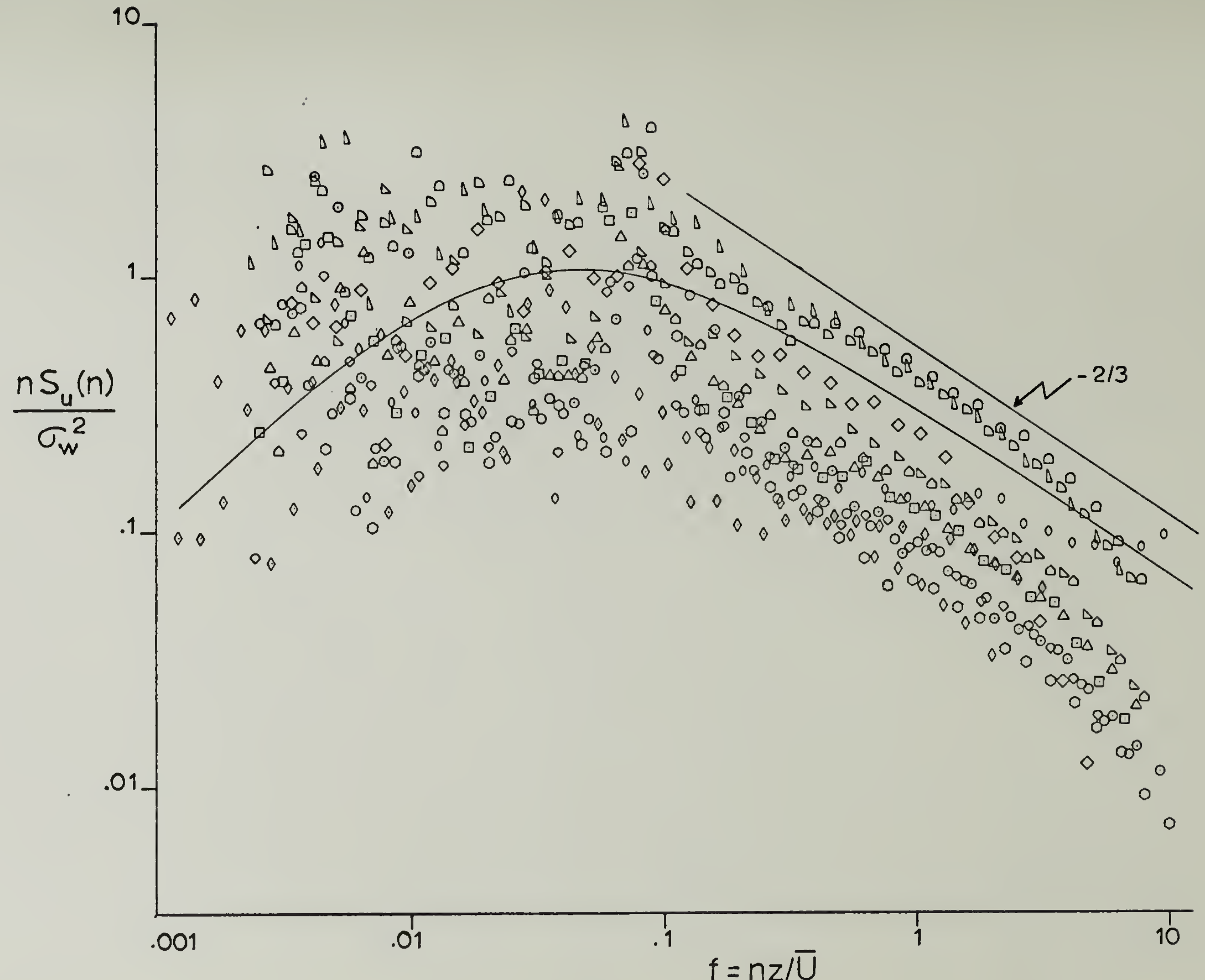

Figure 3. Normalized longitudinal velocity spectra. Curve from Kaimal et al. (1972).

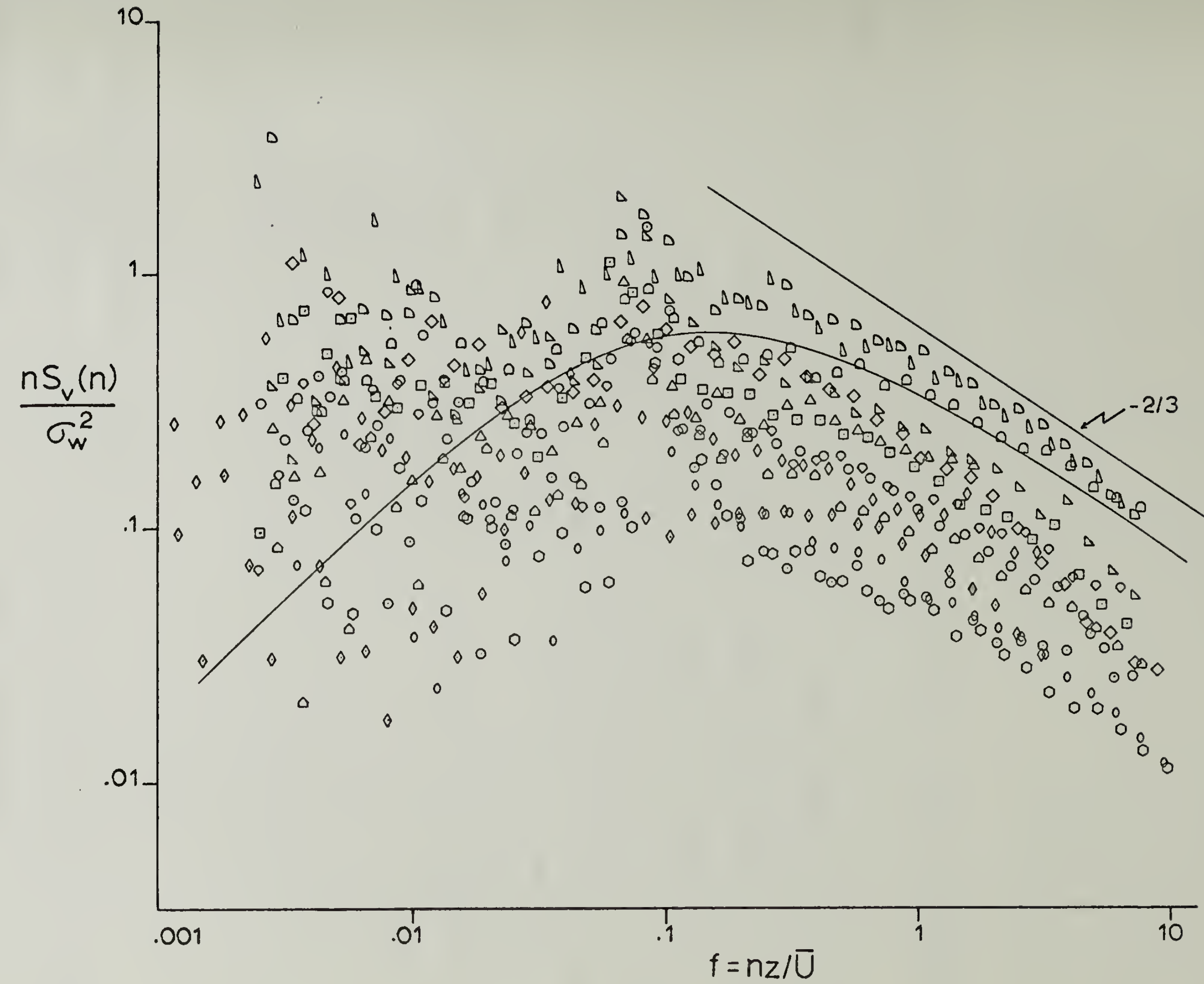

Figure 4. Normalized lateral velocity spectra. Curve from Kaimal et al. (1972).

As a means of making a comparison with spectra over land, the empirically derived equations of Kaimal et al. (1972) were selected for comparison with the analyzed spectra. The expressions,

$$\frac{nS_u(n)}{u_*^2} = \frac{105\ f}{(1 + 33f)^{5/3}} \tag{4.1}$$

$$\frac{nS_v(n)}{u_*^2} = \frac{17\ f}{(1 + 9.5f)^{5/3}} \tag{4.2}$$

were obtained by Kaimal et al. for neutral u and v spectra normalized by u_*^2.

A comparison of these curves with the respective over ocean spectra reveals the slightly lower magnitudes of the two spectra. This is probably the result of normalizing the spectra by the variance of the vertical velocity. The form of the u spectra and the curve from equation 4.1 are nearly identical between $f = .01$ and $f = 6$. The coincidence of the v spectra and the curve from equation 4.2 is limited to a slightly narrower frequency range, $f = .06$ to $f = 4$. Below $f = .02$, the horizontal velocity spectra have a relatively larger amount of energy than that shown by the curves.

B. VERTICAL VELOCITY SPECTRA

The normalized vertical velocity (w) spectra are shown in Figure 5. The scatter in the lower frequencies is significantly greater than that in the higher frequencies. However, the amount of scatter over the entire spectrum, although

still not ideal, is noticeably less than that observed for the horizontal velocity spectra.

The spectra follow the -2/3 law, but only over a narrow frequency range of $f = .9$ to $f = 6$. Above $f = 6$, the spectra drop off as previously noted.

The agreement between Monin-Obukhov similarity theory and observed w spectra has been previously described by Panofsky and McCormick (1960) and Busch and Panofsky (1968). W spectra in Figure 5, above $f = .01$, appear to agree with similarity theory yet the scatter below $f = .01$ presents some difficulty which cannot be explained. A "universal" form suggested by Panofsky et al. (1967)

$$\frac{nS_w(n)}{u_*^2} = \frac{1.075\ f/f_m}{1 + 1.5(f/f_m)^{5/3}} \qquad (4.3)$$

and another suggested by Pasquill and Butler (1964)

$$\frac{nS_w(n)}{u_*^2} = \frac{A\ f/f_m}{(1 + 1.5\ f/f_m)^{5/3}} \qquad (4.4)$$

where f_m is the frequency of the maximum ordinate and A is an undetermined constant, have been plotted on the spectra.

Panofsky et al. (1967) and others have shown f_m to be a function of z/L for the w spectra. In Figure 5, curve a represents equation 4.3 and curve b represents equation 4.4. With regards to both curves, f_m was chosen to be 0.1. A value of 2.0 was chosen for A such that the maximum ordinate for both curves would be approximately equal. The difference observed in the magnitudes between the spectra and the curves at the maximum ordinate are attributed to normalization using the variance of the vertical velocity rather

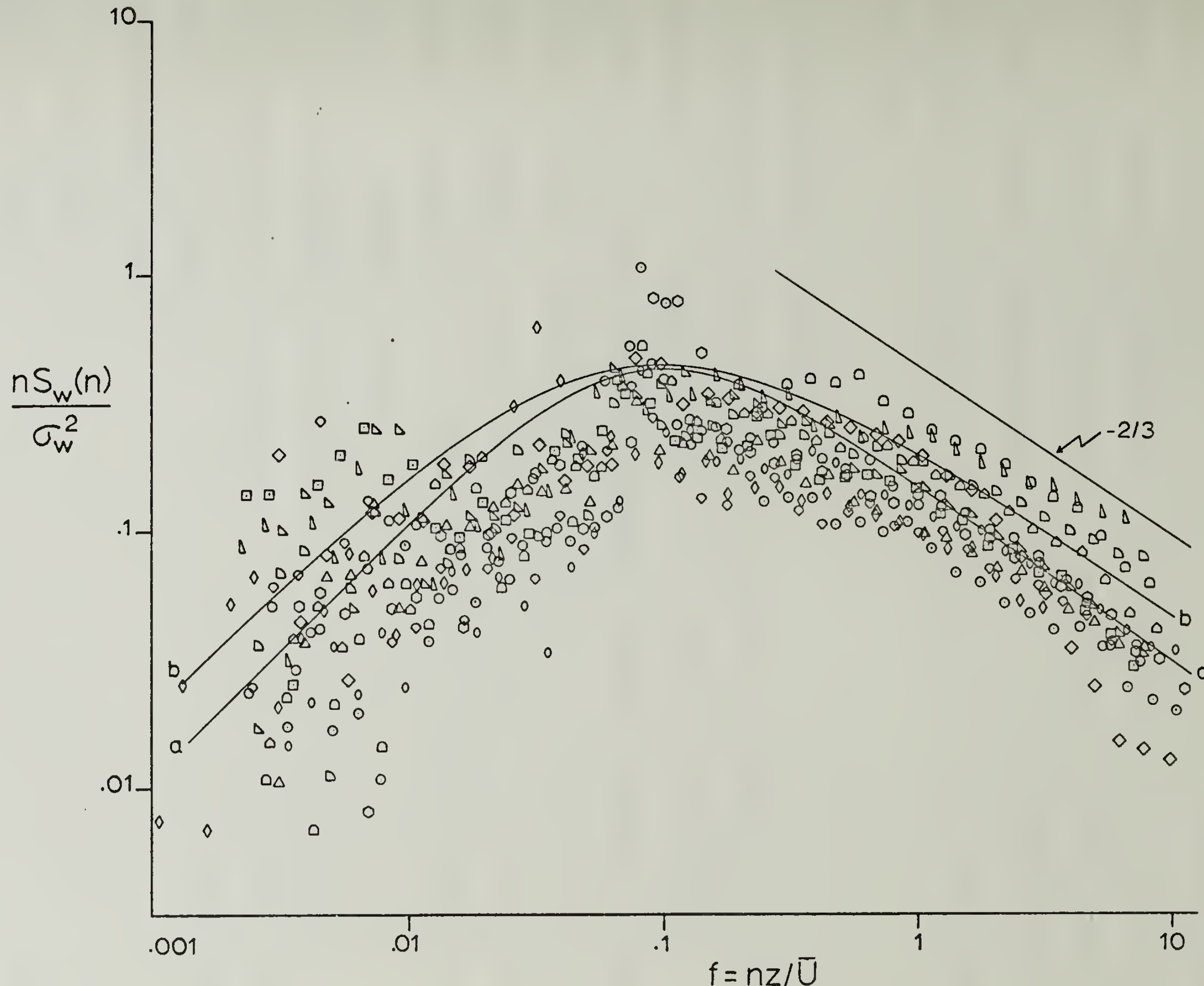

Figure 5. Normalized vertical velocity spectra. Curves: a from Panofsky et al. (1967); b from Pasquill and Butler (1964).

than u_*^2. With a slightly higher choice of f_m and an increase in the magnitude of the spectra, the fit of the curves is quite good with the exception of the region of scatter below f = .01. In comparison with the observed spectra, differences in the curves at high and low frequencies are difficult to evaluate qualitatively due to the scatter in the spectra. However, Busch and Panofsky (1968) viewed differences between the curves to be insignificant. Although somewhat masked by the scatter, there seems to be a relatively larger amount of energy in the spectra when compared to the curves, below f = .02.

C. TEMPERATURE SPECTRA

Temperature (T) spectra are shown in Figure 6. The difference in scatter between low and high frequencies observed in previously discussed velocity spectra is also present in the T spectra. The degree of scatter over the entire spectra is less than that observed for the horizontal velocity spectra and greater than that observed for the vertical velocity spectra.

The straight line drawn on the plot has a slope of -2/3 corresponding to the Kolmogorov -5/3 power law which also exists for temperature spectra. Above f = 2, the spectra follows the -5/3 law.

Results by Panofsky et al. (1968) demonstrated the ability to describe T spectra with Monin-Obukhov similarity theory. The uniformity of the spectra in Figure 6, above f = .02, supports that same conclusion. The seemingly

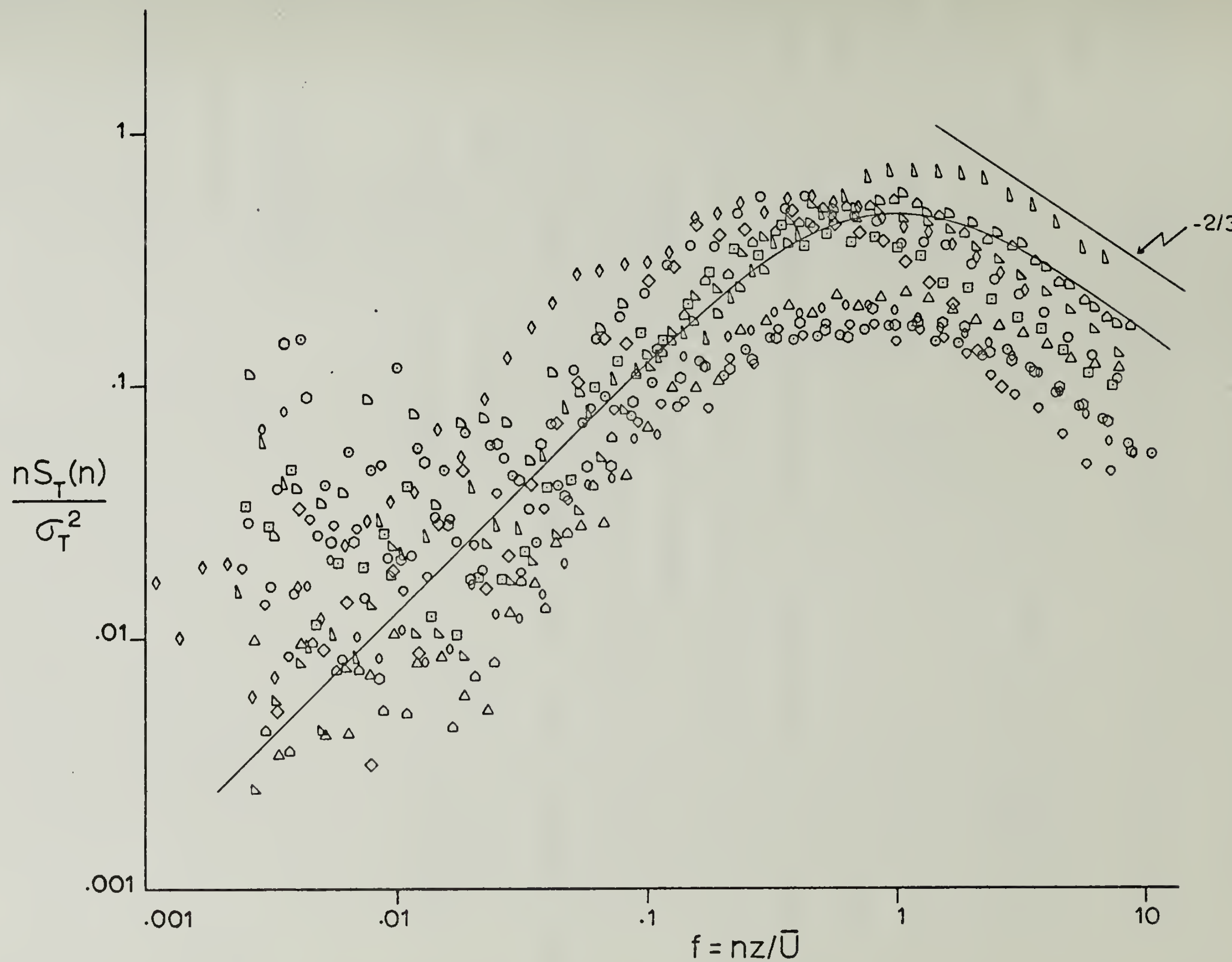

Figure 6. Normalized temperature spectra. Curve from Panofsky et al. (1968).

unexplainable scatter below $f = .02$ is consistent with previously discussed velocity spectra. The curve constructed from the relation

$$\frac{nS_T(n)}{T_*^2} = \frac{2.5\ Y_m\ f/f_m}{1 + 1.5\ (f/f_m)^{5/3}} \qquad (4.5)$$

where Y_m is the maximum ordinate, has been plotted in Figure 6.

Panofsky et al. (1968) found both Y_m and f_m to be functions of z/L. The values chosen for Y_m and f_m were 0.5 and 1.0 respectively. The ability to arbitrarily select values for Y_m does not allow for any qualitative comparison between T_*^2 and the variance of temperature. The forms of the T spectra and the curve are strikingly similar with only a slight deviation in slope between $f = .02$ and $f = .1$. However, a significant difference exists between the f_m observed by Panofsky et al. (0.1) and the f_m chosen here (1.0) where both are plotted over comparable ranges of z/L. The relatively larger amount of energy in the spectra below $f = .02$ is again evident.

D. UW COSPECTRA

Normalized uw cospectra are shown in Figure 7. The scatter in the low frequency range, comparable to that found in the u spectra, is significantly greater than the scatter in the high frequency range. The extent of the scatter in the high frequency range may have decreased by the previously discussed omission of estimates from seven periods.

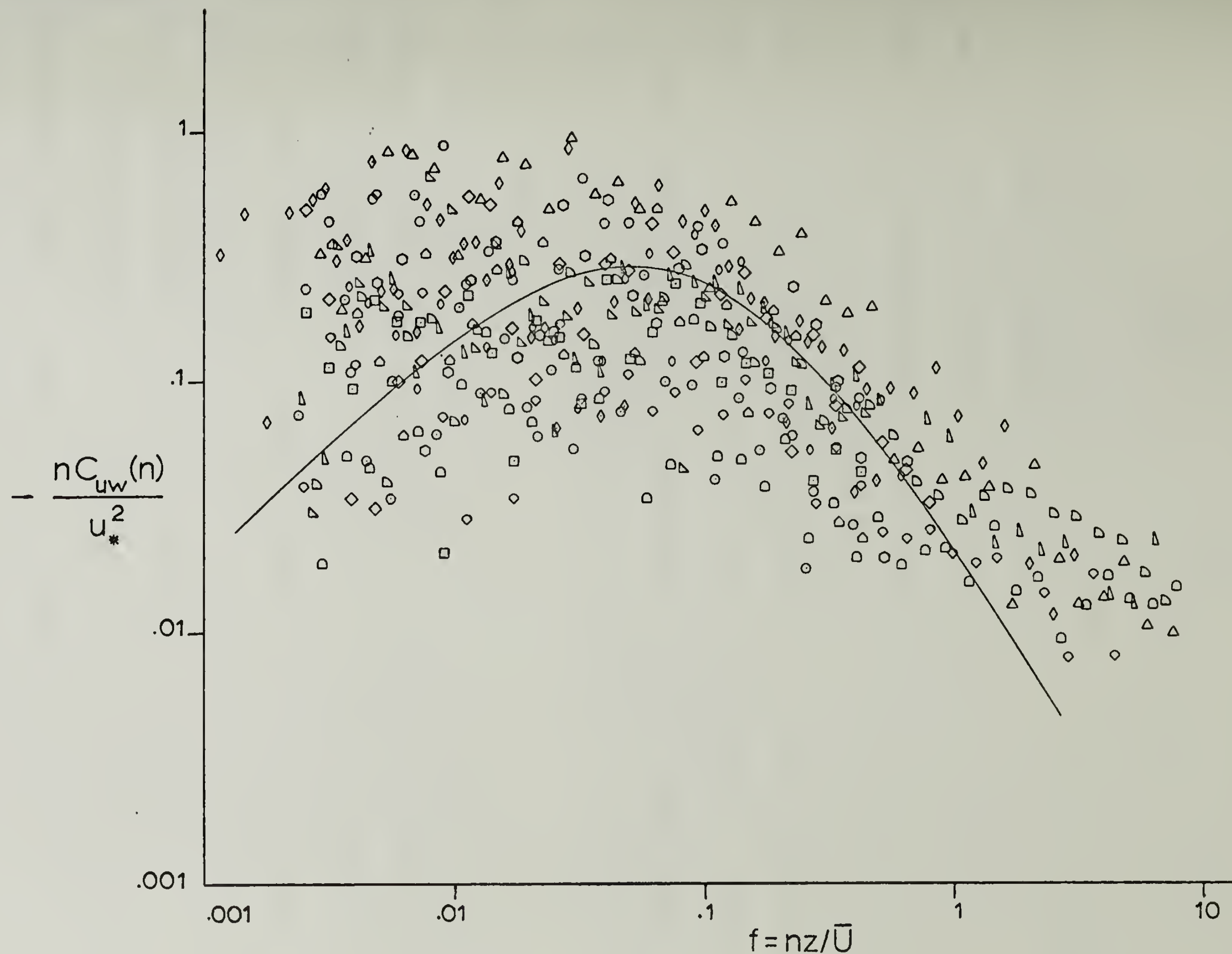

Figure 7. Normalized uw cospectra. Curve from Panofsky et al. (1968).

Evidence verifying the description of uw cospectra utilizing Monin-Obukhov similarity theory has been presented by Panofsky et al. (1967). The dispersion below $f = .1$ would not indicate an agreement with the similarity theory. A comparison between an expression derived by Panofsky et al.

$$\frac{nC(n)}{u_*^2} = \frac{f/f_m}{(1 + 0.6\ f/f_m)^{8/3}} \qquad (4.6)$$

and the plotted uw cospectra is made in Figure 7. Panofsky et al. found the expression applicable to both uw and wT cospectra. f_m was chosen to be .05 whereas Panofsky et al. chose .02 for stable air. The magnitudes of the cospectra and the curve are comparable between $f = .02$ and $f = .2$. The location of the maximum ordinate for the cospectra is masked by the scatter in the lower frequencies. Nevertheless, the under-estimation, by the curve, of the magnitudes of the cospectra at both high and low frequencies is quite evident.

E. WT COSPECTRA

Normalized wT cospectra are shown in Figure 8. The scatter in the lower frequencies is again greater than in the higher frequencies. In comparison to the uw cospectra, there is a larger amount of scatter throughout the wT cospectra. Also, the point plots of the wT cospectral estimates are not distributed evenly within the region of scatter.

Results obtained by Panofsky et al. (1968) suggested wT cospectra could be described by Monin-Obukhov similarity theory. The form suggested by Panofsky et al., equation 4.6, is represented by the curve in Figure 8. Although f_m was

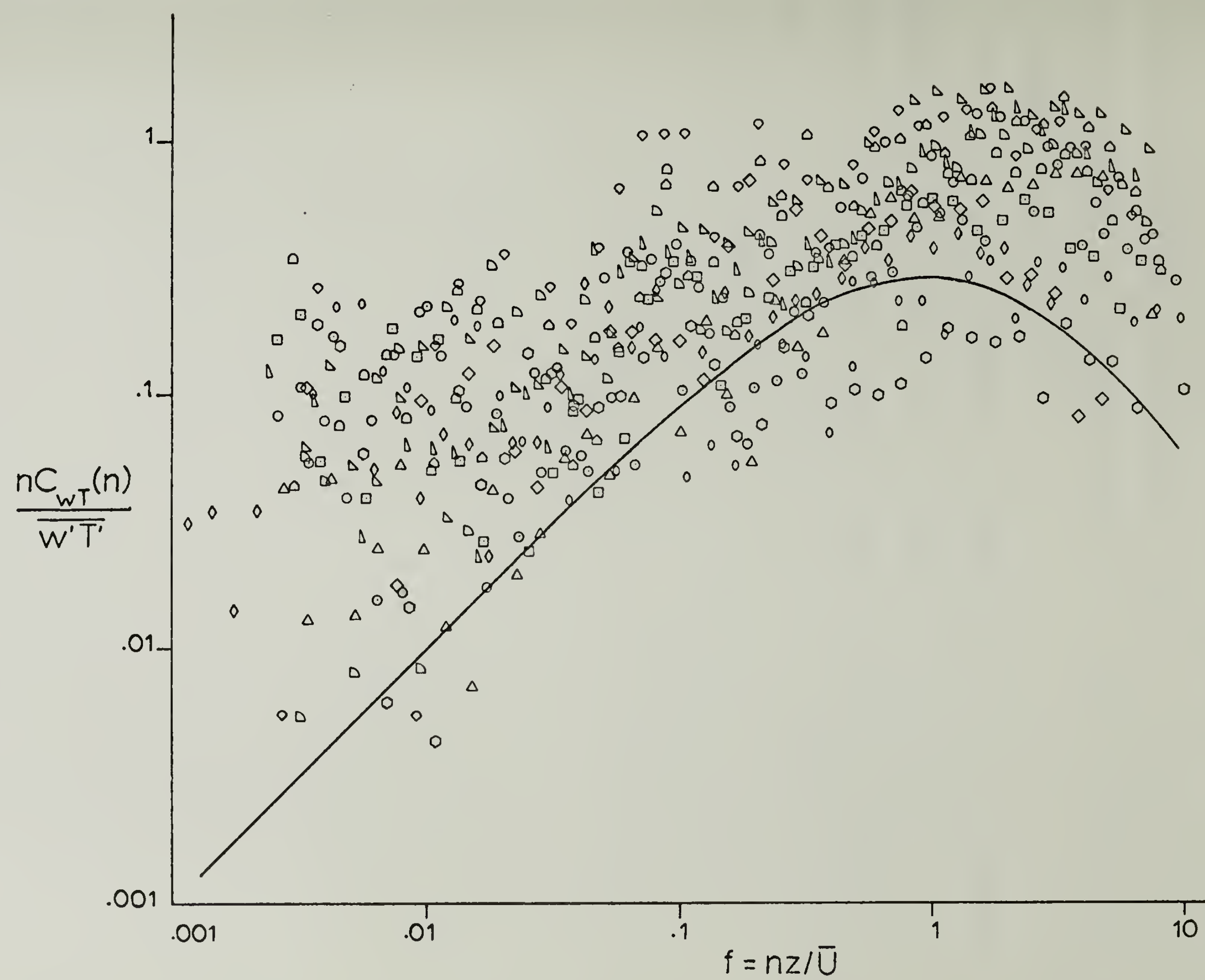

Figure 8. Normalized wT cospectra. Curve from Panofsky et al. (1968).

chosen to be 1.0, a more accurate value would be 2.0. Even though the form of the curve is quite similar to that of the wT cospectra, the magnitudes predicted by the curve are significantly less than those of the cospectra. In addition to the difference in magnitudes, the value of f_m found by Panofsky et al. (.2) is significantly less than the value of f_m indicated by the wT cospectra (2.0). A relatively larger amount of energy is present below $f = .02$ in the cospectra as compared to the curve.

The similarity between wT cospectra and uw cospectra as suggested by Panofsky et al. (1968) is not evident. The wT cospectra has a significantly larger amount of energy in the high frequency range. However, the two cospectra do tend to have similar forms.

V. SUMMARY AND CONCLUSIONS

Normalized spectra and cospectra were computed for turbulence data obtained over the ocean during BOMEX. Results from 15 periods were compiled for the u, v, and w spectra and the uw and the wT cospectra.

Each set of normalized spectra/cospectra was examined for consistency with regard to convergence in the high frequency range. Significantly more scatter was found in the frequency range below $f = .01$ for v, w, and T spectra; $f = .04$ for uw and wT cospectra; and $f = .05$ for u spectra than was found in the high frequency range. Scatter over the entire frequency range for all spectra and cospectra was greater than expected.

Kolmogorov's -5/3 power law was followed by both the u and w spectra but over differing frequency ranges. The high frequency limits were similar due to the numerical filtering during analysis of the data. However, the lower frequency limit for the u spectra was at $f = .2$ whereas the lower limit for the w spectra was at $f = .9$. This reflects the influence of the boundary on the w spectra. In the normalized coordinates used, the v spectra indicates a slope on the order of -1/2. Results for the T spectra were inconclusive.

The use of Monin-Obukhov similarity theory to predict the forms and magnitudes of spectra and cospectra was examined utilizing equations suggested by Panofsky et al. (1967),

Panofsky et al. (1968), and Pasquill and Butler (1964). Similarity theory does not appear to describe the u and v spectra. However, the w spectra showed an excellent correlation with the suggested universal forms. Although the form suggested for the T spectra fit the computed spectra extremely well, the difference noted in the f_m values indicates the presence of a variable not accounted for by similarity theory. Phelps and Pond (1971) suggested an influence by radiative transfer. The form suggested for the uw cospectra did not adequately describe the computed cospectra. The computed wT cospectra tended to agree with the form of the suggested similarity theory description but the difference in magnitudes and f_m values indicate a conclusion similar to that reached for the T spectra.

All of the computed spectra and cospectra were either compared with empirical or similarity theory descriptions derived from over land spectra. In every case, the computed spectra and cospectra had a relatively larger amount of energy in the frequencies below $f = .02$.

A comparison of the uw and the wT cospectra showed a significant difference between the two cospectra. This tends to verify the previously discussed observations made by Kaimal et al. (1972) who concluded that small eddies transport heat more effectively than momentum and large eddies transport heat less effectively than momentum.

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ABSTRACT

Spectral and cospectral analyses are performed on turbulence data obtained over natural ocean waves during BOMEX. Results are obtained for normalized spectra and cospectra. Significant scatter is observed throughout the spectra and cospectra with a larger degree of scatter in the low frequency range. Kolmogorov's -5/3 power law is found to describe the longitudinal and vertical velocity spectra in the high frequency range. However, it is not applicable to the lateral velocity spectra while results for the temperature spectra are inconclusive. Monin-Obukhov similarity theory well describes the vertical velocity spectra yet its application to horizontal velocity spectra is doubtful. Similarity theory does not seem to adequately describe the uw cospectra. Results from comparing similarity theory to temperature spectra and wT cospectra indicate the presence of an influence not accounted for by similarity theory. When compared, uw and wT cospectra are found to be significantly different. All computed spectra and cospectra are found to have a relatively larger amount of energy in the low frequency range than their respective over land spectra and cospectra.

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